JOURNAL OF AIRCRAFT
Vol. 42, No. 6, November–December 2005

Movable Tip Strakes and Wing Aerodynamics

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A wind-tunnel study of the effects of the addition of movable tip strakes on the aerodynamic characteristics of a rectangular wing model has been conducted. This is a new application of the strake concept for modifying the flowfield around a wing. The addition of sharp-edged slender delta-wing-shaped strakes significantly modified the flow pattern in the vicinity of the wing through generation of vortex lift. The strakes improved the lift-to-drag ratio of the baseline wing by as much as 23%. The method can have potential for lateral control too. Based on limited flow-visualization results, it appears that the strakes favorably influence the near-field roll up of the wing trailing vortices. The approach warrants additional investigations using more advanced measurement and flow-visualization techniques.

Nomenclature

AR	=	b^2/S aspect ratio
b	=	span, mm
C_D	=	wing drag coefficient
C_L	=	wing lift coefficient
c	=	chord, mm
d	=	angle relative to wing chord plane, deg
q	=	$\frac{1}{2}\rho_\infty V_\infty^2$ freestream dynamic pressure, kPa
R_e	=	$\rho_\infty V_\infty c/\mu_\infty$ Reynolds number based on chord
S	=	reference area, mm^2
s	=	semispan, mm
V_∞	=	freestream velocity, m/s
x, y, z	=	aerodynamic axes
α	=	angle of attack, deg
μ	=	absolute viscosity, N · s/m^2
ρ	=	air density, kg/m^3

Subscript

s	=	strake

Introduction

WING strakes are fixed additional areas located at the wing-fuselage juncture at the wing leading edge. They are also referred to as wing-root leading-edge extensions (LEX) and together with the main wing as hybrid wings. By creating strong vortical flows over the wing top surface, the strakes generate additional lift, the vortex lift that is particularly significant at flight conditions when the wing approaches the critical angle of attack. By doing so, the airplane's lifting and longitudinal stability characteristics are improved. Wing strakes have been known for a number of years to improve the aerodynamic characteristics of wings of various classes of airplanes. Some particularly successful examples of application of strakes are provided by the F-5, F-16, F/A-18, and MiG-29 aircraft. The author was involved in retrofitting strakes to a transonic fighter aircraft, the J-22 Orao (the Eagle), in the late 1970s while with the Aeronautical Institute, Belgrade, Yugoslavia.

Review of Past Research on Aerodynamics of Strakes and Similar Devices

Strakes have been studied extensively since the 1970s as a means for improving the aerodynamics of moderately swept wings. Given next are some highlights of that work in a chronological order. The list however is not intended to be complete. Also included are vortex flaps, wing-tip sails, and other similar devices deemed relevant to the present study.

Polhamus proposed a method for prediction of vortex lift of sharp-edged delta wings at low speeds based on a leading-edge suction analogy.[1] He found that the vortex lift is relatively independent of aspect ratio in the range of usual interest. In his excellent treatise of the aerodynamic design and development of the Anglo–French Concord, Morgan pointed out the differences between the classical attached-flow model and the controlled separation as the main feature of the Concord-like wing.[2] With a very low-aspect-ratio wing, a free vortex layer springing from near the leading edge can roll up into two powerful vortices over the wing surface. These vortices dominate the flow around the wing.[2] Lamar extended the leading-edge suction analogy of Polhamus[1] to wings with side edges.[3] Rehbach applied a singularities method to plane and cambered delta wings and wings with curved leading edges.[4]

Küchemann presented various methods for improving the design of swept wings.[5] He proposed a cranked wing, which comprises a usual swept wing and a highly swept wing having a sharp leading edge. Moss summarized the research work on wings with strakes in the United Kingdom.[6] He quoted results from experimental research of interest to design engineers relevant to incorporating strakes in combat aircraft configurations. Stuart describes the development of the F-5E wing starting with the T-38 planform and points out that the addition of a LEX, having an area equal to 4.4% of the baseline wing area, provided an increase in the wing $C_{L\max}$ by 38%. Also the maximum trimmed angle of attack, important for air combat effectiveness, was increased by approximately 22% (Ref. 7).

Spillman found that when small cambered and twisted surfaces, called sails, were fitted to the tips of a wing, its induced drag was reduced by up to 30% (Ref. 8). The sails were able to turn the flow from lower- to the upper-wing surface from spiral to near streamwise direction. Luckring studied the effects of variations in strake span and wing sweep on the aerodynamic characteristics of a research model.[9] He reported that appreciable levels of lift have been shown to arise from the mutually beneficial strake-wing interference. Lamar reports on the progress made in improving the transonic maneuverability of strake-wing configurations.[10] The procedure he described produced a gothic strake, which, in conjunction with a wing body, creates a well-behaved vortex system resulting in a flat postmaximum lift variation with increasing angle of attack.

One of the most successful applications of the strake concept to a wing design is that by the Northrop Company in the design of the YF-17 aircraft, which subsequently became the F/A-18. The company developed the hybrid wing concept in the late 1960s and applied it to the YF-17 prototype development program in 1972.[11] A sharp highly swept wing LEX causes flow separation at low angles of attack in the way typical of delta wings. This separated flow forms

Received 15 August 2003; revision received 20 January 2005; accepted for publication 24 January 2005.

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a vortex along and above the wing leading edge resulting in a flow system that is stable up to relatively high angles of attack.

An extensive study of a wing with a strake including surface oil flow visualization, force measurements, and pressure measurements was conducted by Liu and his associates at low, transonic and supersonic speeds.[12] They identified four distinct flow patterns on a wing with a strake and concluded that the flow on the wing upper surface is affected and controlled by the formation, development, and breakdown of the strake vortices. An exploratory wind-tunnel investigation to evaluate the potential of a hinged-strake concept for enhanced controllability in poststall flight was presented by Rao and Huffman.[13] The concept aims to control the strake load independently of angle of attack and sideslip by varying the anhedral angle of the strakes hinged along the root chord. They concluded that hinged strakes appeared to be a promising and practical means of combining the maneuver benefits of conventional strakes in the well-behaved vortex regime, with enhanced controllability at higher angles of attack when vortex breakdown causes stability problems.[13]

Lamar and Frink tested a series of strakes in a wind tunnel.[14] They concluded that the lift and pitch data were reasonably well predicted by an extended suction analogy method and that the accuracy with which lift was predicted improved with increasing strake area.[14] According to Peake and Tobak, the LEX provides additional lift produced by the vortices generated on the highly swept sharp leading edges.[15] This additional lift increases the maximum lift, which is available at higher angles of attack, and it can be used beneficially to extend combat-maneuvering capabilities. Lamar and Campbell presented an extensive study of various devices employing leading-edge vortical flows as well as the interactions of these vortical flows with neighboring surfaces.[16] Their paper summarizes the work in this area conducted or sponsored by NASA Langley Research Center from 1978 to 1983. The concepts discussed include wing-strake combinations, LEXs, and vortex flaps. Erickson and Gilbert investigated the vortex flowfield interactions on a fighter aircraft at high angles of attack.[17] Their results revealed the potential for strong interactions between forebody and LEX vortices. They also suggest that the presence of a LEX vortex alters the wing spanwise lift distribution.[17]

Rao addressed the progress in vortex-control applications for alleviating the adverse consequences of three-dimensional separation and vortical interactions on slender-body/swept-wing configurations.[18] One example consisted of hinged strakes used to avoid vortex breakdown effects. He concluded that hinged strakes of suitably chosen size and anhedral setting can provide problem-free high-alpha maneuvering without sacrificing the maximum lift capability of the conventional fixed strakes.[18] In a different study Rao investigated the potential of planform modification and hinge-line relocation to improve the performance of vortex flaps on a delta wing.[19] He found that spanwise segmentation and chord tailoring of the flap segments enabled maintaining the vortex on the outboard flap surfaces to higher angles of attack.

In his classic paper Polhamus reviewed the benefits of slender wings applicable to military aircraft.[20] He outlined the research up to that point conducted in this vast area primarily at NASA Langley Research Center but also by others. Two major categories were addressed: the variable-sweep wings and the hybrid wings. In the latter category, two concepts are discussed: vortex-lift strakes and slender cranked wings. He concluded that for fixed-planform slender-wing aircraft a design philosophy in which controlled separation-induced vortex flow is combined with the classical attached flow expands the performance capabilities.[20] Stinton describes the slender-delta concept as being essentially two large wing tips joined together at the centerline.[21] He explains that this wing makes use of the separated vortex flow shed from what are now the leading edges of the wing to generate large, nonlinear lift increment. According to him, the generation of such lift-producing vortices at low speeds delays the stall in the classical sense, so that the wing can reach extremely high angles of attack equal to or greater than 40 deg.

Bobbit and Foughner tested a series of pivotable strakes in combination with a swept wing and a cranked delta wing to examine their potential for providing pitch control at high angles of attack.[22] They found that strake deflection generally had a significant effect on moment while lift-to-drag ratio (L/D) changed very little. Rao and Campbell reviewed a selection of results and discussed several concepts for manipulation of vortices resulting from flow separation from highly swept leading edges and slender forebodies at moderate to high angles of attack and their potential for improving the aerodynamic performance of advanced supersonic configurations.[23]

Various design features of wings with separated flow, as contrasted with the classical high-aspect-ratio wing flows, are discussed by Huenecke.[24] In particular, the lift characteristics of the two types of wings were considered. Unlike the lift curve for a wing with a large aspect ratio, which remains linear through the onset of the flow separation at large angles of attack, a slender delta wing, as an example of a low-aspect-ratio wing, already shows a nonlinear increase in lift at small angles of attack, and the curve is significantly flatter. The highly swept delta-wing configuration has been used successfully in the design of various fighter aircraft. Equally attractive is a configuration having a lower sweep and a larger aspect ratio. They both have their advantages and disadvantages. A wing with strakes is a combination of the two concepts. It has been used effectively to meet ever-growing requirements for increased maneuverability in aerial combat. Huenecke further discusses in some detail the improvements as a result of the addition of the strakes and provides examples of successful incorporation of strakes in wing design, notably the F/A-18 and the F-16 aircraft.

The use of leading-edge vortices to improve the transonic maneuverability of a fighter aircraft (a British Aerospace Harrier model) from Ref. 6 is discussed in Ref. 25. An inboard strake was added to the existing model at the wing leading-edge–fuselage junction. Oil flow visualization showed that the flow separation in the inboard half of the wing had been eliminated. The resulting performance improvements include a significant delay of stall, a removal of wing-drop tendency, and a greatly reduced buffet level.[25]

Lamar reviews a variety of vortical flow control devices from both the experimental and analytical point of view.[26] He classifies them as either fixed or movable. Among the fixed devices he discusses strakes, LEXs, and vortex generators. It is pointed out that the increase in $C_{L,\max}$ caused by the addition of the strakes is significantly higher than what could be expected from an equivalent wing area enlargement. Among the movable devices, Lamar discusses articulated strakes as an alternative for improving usable lift at high angles of attack, as both lifting and control devices. This instance is mentioned because of its relevance, although tangential, to the study presented in the present paper. The hinged strakes were articulated to suppress the strake vortices, thus eliminating or reducing the effect of vortex breakdown.[26] The strakes were hinged along the line fuselage-strake and thus could be deflected in the yz plane.

Spillman concluded that, for a given wing span and aircraft weight, wing-tip sails reduce the fuel used and the required wing strength at all flight speeds.[27] He also suggested using tip sails for roll control, reducing the size of the ailerons, and thus allowing a greater flap span.[27] Vijgen et al. studied the performance benefits of a high-aspect-ratio (Æ) unswept wing with sheared tips.[28] The sheared tips had large sweep angles and low taper ratios and were coplanar with the main wing. The computational and experimental results agreed well and showed that the sheared tips could reduce induced drag at cruise and climb conditions. They attributed the induced drag improvement to the deformation of the wake and the altered spanwise load distribution.[28]

Ma studied experimentally wing-tip strakes with the aim of improving the L/D of rectangular and tapered wings of various Æs.[29] The strakes were of triangular design having the trailing edge either perpendicular to the root chord or at an angle between 30 and 60 deg relative to it. It is not clear from the paper whether or not the leading edge was made sharp. He found that the strakes did increase the wing L/D between 7 and 26.6%, with the planar strakes being less effective than the strakes installed with a dihedral. Xie-yaun et al. presented computational results for the rolling up of the leading-trailing-edge vortex sheets for delta and double-delta wings using a two-dimensional discrete vortex method.[30] These numerical results were found to be in good agreement with experiments.

According to Whitford, one of the major considerations in wing design throughout the development of aerodynamics has been the avoidance of flow separation.[31] With the design of the Concorde supersonic transport,[31] this "time-honored reverence for attached flow was called in question." This has had an impact on fighter aircraft design since the 1960s. To ensure an acceptable level of low-speed performance, the wing leading edge is made sharp to trigger flow separation along its entire length. This produces a very stable vortex system that propagates over the wing, thus enhancing its lifting capability. A disadvantage of the separated flow is the accompanying loss of leading edge thrust, which leads to increased drag at low angles of attack. As an example of successful use of strakes, he cites the General Dynamics F-16 fighter aircraft. The adopted strake configuration was a result of joint work between NASA and General Dynamics. Also included was the British Aerospace Harrier.

In his widely accepted textbook on aircraft design, Raymer[32] presents strakes or LEXs as a means for increasing lift for combat maneuvering. He describes them as being similar to dorsal fins used on vertical fins. Like dorsal fins, the LEX at higher angles of attack produces a vortex that delays flow separation on the wing and stall. He cautions, however, that this device tends to promote pitch-up tendencies and thus should be used judiciously.[32] The possibility to obtain better aerodynamic performance from a wing with a nonplanar outboard wing form than from a wing with a planar outboard form was investigated by Naik and Ostowari.[33] The results showed that it was possibly to improve the wing efficiency with the nonplanar forms, and furthermore, in some cases, the advantage was such that it overcame the added skin-friction drag caused by the increased wetted area.

Del Frate et al. report extensive flow visualization and pressure distribution studies conducted on the NASA F-18 high-alpha research vehicle (HARV) to document the characteristics of the forebody and the LEX vortices.[34] The results indicated that the F-18's flowfield is substantially dominated by the vortices generated by flow separation at moderate to high angles of attack from the forebody surface and at the sharp leading edge of each LEX. The LEX vortex cores are tightly wound and extend downstream until experiencing vortex core breakdown.[34] Rao presents the progress of investigations of several techniques for vortex control.[35] A portion of his paper deals with the twin vertical tail buffet alleviation on the F-18 aircraft. He points out that highly swept strakes integrally affixed to the leading-edge/fuselage junction (or LEXs) were the first usage of custom-generated large-scale vortices for augmenting the maximum lift capability of trapezoidal wings, as employed on the F-16 and F-18 fighters. Rao proposes a controllable LEX to directly influence the vortex production mechanism and thus its interaction with the wing and the tail.[35]

Staufenbiel and Vitting first looked into the formation and structure of wing-tip vortices and compared their results with laser Doppler velocimetry (LDV) measurements.[36] Next, they discussed the effect of lift distribution on maximum circumferential velocity of trailing vortices. Finally, they investigated several devices for potential vortex alleviation. These included artificially destabilizing the vortex, inducing breakdown of the vortex core, and spreading the vorticity of trailing vortices. The second method—the one involving induction of vortex core breakdown—is relevant to the present study and is thus briefly reviewed here. The starting point for this approach lies in the fact that delta wings at high angles of attack create leading-edge vortices that can break down very closely behind or even above the wing. In general, this type of vortex breakdown is accompanied by a drastic change of the flow pattern.[36] This gave rise to a supposition that it would be possible to stimulate the tip vortices of conventional wings to break down. For this purpose they used a wing with a half-delta tip and investigated it in a water tunnel. The half-delta consisted of a sharp-edged plate extending the lower flat side of the wing profile. While the reference wing generated a small core radius, the half-delta equipped wing created vortices with larger cores by a factor of almost three, and the maximum circumferential velocity was reduced by about 35%.

Brown et al. conducted wind-tunnel tests to measure the mean and unsteady forces and moments and pressure distributions on the forward fuselage, the LEX, and fins in the LEX vortex wake of a 6% model of the F/A-18 aircraft.[37] They state that the LEX has been credited with a 22% increase in $C_{L\max}$ and an increase in the angle for $C_{L\max}$ by 10 deg. Traub and Nurick conducted an experimental investigation of sheared tips modified to form a wing-tip vortex flap.[38] The flap was formed by rotating a leading-edge extension either above or below the plane of the wing. They found that deflecting the tip flap had a similar but opposite effect to that of deflecting a trailing-edge flap as far as the effect on the zero-lift angle of attack is concerned. Lee and Valerio used oil flow visualization in a wind tunnel to study the structure of the flow around the LEX and the LEX fence of the F/A-18.[39] They identified a complex flow structure comprising several vortices. An experimental investigation into the effects of strake vortex flaps on the aerodynamic characteristics of a wing-strake was conducted by Traub and Merwe.[40] They found that the L/D increased for all flap deflections compared to the planar strake for moderate and high lift coefficients.

Traub conducted an experimental investigation into the effects of delta planform tip sails (DPTSs) on the performance of a planar rectangular wing.[41] The DPTS is a small wing-tip-mounted device similar to a conventional tip sail, but having a slender planform. The sails were made of thin plate and had sharp leading edges. The sail's chord line corresponded to that of the wing. The largest improvement in lifting performance was obtained with a DPTS with a leading-edge sweep angle of 70 deg, which increased the lift-curve slope by 7.94% over the basic wing and $C_{L\max}$ by 4.94%. Increasing the DPTS leading-edge sweep angle and taper ratio resulted in an increase in wing efficiency.[41] In a different study Traub investigated the effects of DPTS incidence and arrangement on performance of rectangular wings.[42] His results suggested that, based on equal aspect-ratio comparison, sails have a negligible effect on lifting performance, except for a moderate increase in the maximum lift coefficient. He also found that using only one sail per wing tip resulted in a reduction in performance compared to the basic wing.[42]

According to Whitford, in the late 1960s, the U.S. Navy launched a major effort to improve the combat effectiveness at high angle of attack of several aircraft. Significant improvements to combat maneuvering have been made via leading- and trailing-edge devices. He describes examples of performance improvements of several airplane designs combining attached flow with controlled separation via LEXs and strakes. He also points out that, on the negative side, the separated vortex flow increased drag at lower angle of attack and caused buffet of vertical fins.[43]

Kuethe and Chow[44] point out that at highly swept leading edges, such as those represented in delta wings, leading-edge separation occurs. This gives raise to a vortex having an axis slightly aft of the leading edge. They further state that the measured lift on these configurations has been found to be considerably higher than the potential lift.[44] This lift increment, which they referred to as the vortex lift, is generated through the action of the leading-edge vortices altering the existing flow and pressure distribution. In addition to the strakes being able to generate significant additional lift themselves, the strake-generated vortices retain their organized structure while moving over main wing, resulting in further favorable interference effects and additional lift increments.[44]

An experimental investigation into the ability of planar and nonplanar wing-tip strakes to improve the performance of a rectangular wing having sheared tips was conducted by Traub and his associates.[45] The strake planform, leading-edge sweep, and anhedral were varied. The strakes were fixed relative to the wing. Their results showed that planar strakes caused minimal drag penalties at low lift coefficients, while improving the wing efficiency up to 12.8%. Nonplanar strakes significantly improved the wing efficiency but at the expense of a substantial increase in the minimum drag coefficient. Flow visualization showed that the wing-tip vortex system consisted of four vortices, two on the strake and two above the wing tip.[45] The effect of flap hinge-line location on the performance of leading-edge vortex flaps was studied experimentally by Rinoie and Kwak.[46] They found that the best L/D was achieved when the delta wing has vortex flaps with a relatively small spanwise length.[46]

Bertin refers to these additional, highly swept areas ahead of the main wing as leading-edge extensions.[47] He discusses the mutual benefits derived from strake/wing combinations in terms of the elements of this interaction as presented by Lamar and Frink.[14] Schultz and Flack investigated experimentally the use of fillets at the strake-wing juncture for controlling the vortex flow of a wing-strake configuration using a flat-plate and a three-dimensional model.[48] They found that linear fillets when used in conjunction with the flat-plate model significantly increased the wing lift coefficient at moderate–to-high angles of attack. However, when applied to the three-dimensional model the fillets had little effect on the lift coefficient.[48]

Beyers presented a survey of the experimental efforts toward defining the aerodynamic characteristics of the F/A-18 aircraft.[49] The F/A-18 poststall maneuvering, he states, is dominated by forebody/LEX vortex interactions at moderately high angles of attack.[49] Sohn et al. investigated experimentally the development and interaction of vortices over a yawed delta wing with a LEX for varying angles of attack and sideslip angles.[50] Their study confirmed the profound effect of sideslip on the vortex structure and interactions of a LEX-equipped delta wing.[50] Computational investigations of the buffet characteristics of the F/A-18 twin vertical tails interacting with the strakes-generated vortices were conducted by Sheta.[51] The results found were in close agreement with the data from several flight and wind-tunnel tests over a wide range of high angles of attack.

Rationale for Present Study

The motivation for this study has been two-fold. First, it appeared that having strakes that can rotate about an axis parallel to the wing spanwise axis could provide additional amounts of lift, positive or negative depending on the strake deflection and the main wing angle of attack. This would provide an additional control variable allowing for the strakes to be brought to their optimal angle of attack independent of the wing setting. None of the research efforts reported so far and briefly reviewed have taken this approach. Although hinged[13,18,22,26,35] strakes have been studied before, their location and rotation relative to the wing have been radically different from that proposed in the present study. Fixed nonplanar outboard wings[23] and fixed tip strakes[29] and sails[41] have been proposed before. Furthermore, the reported movable devices located in the tip region, the tip sails,[42] have been on the order of approximately 4.5% of the wing area or less, or about four times smaller than the movable tip strakes presented here, and they have been intended to explore the existing flow pattern in the region of their placement rather than to significantly modify the flow by their own presence. Only a moderate improvement in $C_{L\max}$ was found. Using one sail per wing tip even resulted in a reduction in performance compared to the basic wing.[42]

Second, as proposed by Staufenbiel and Vitting[36] it seemed reasonable to expect that the addition of strake-generated vortices and their breakdown in the wing-tip region could influence the roll up of the wing trailing wake vortices. They used fixed tip strakes. The introduction of a new control variable, the angle of setting of the strakes relative to the wing, as proposed in the present study, seemed to make this argument even more plausible. Then several new questions arise including: Can having this additional control variable be used to improve the aerodynamic performance of the wing at cruise conditions? Can the breakdown of the strake vortex and its potential negative effect on the strength and thus longevity of the wing trailing vortex be somehow quantified, at least in the near field? The objective of this study has been to address these questions.

Experimental Setup and Procedure

This study has been conducted in an open-circuit wind tunnel capable of producing flow speeds up to 45.7 m/s. The test section has dimensions of 305 × 305 mm. The lift and drag forces are measured using a dynamometer-type balance comprising two linear variable differential transformers. A more detailed description of the tunnel and its instrumentation can be found in Ref. 52. All of the data points were taken at a dynamic pressure of 0.625 kPa, so that the measured lift forces would remain within the range recommended by the tunnel manufacturer. The resulting Reynolds number of the flow was kept constant at 0.225×10^6. The angle of attack of the wing is set using a simple method of visually matching the wing side view (when looking from the left wing tip toward the centerline along the y axis) with a NACA 4412 contour scribed on a 4-in. (101.6-mm) plug fitting into an access aperture on the test section.

The model used in the study consisted of a rectangular wing having a NACA 4412 airfoil, a chord of 99 mm, a span 161 mm, and thus an aspect ratio of 1.62. This model is referred to as the baseline wing. To facilitate more complete examination of the flowfield around the model, the baseline wing was at times equipped with one or two sets of tufts, 11 tufts each for flow visualization. The first series was used for visualizing flow separation from the wing, and they are referred here to as the flow separation tufts (FSTs). These tufts were placed on the right semispan of the wing's suction surface along a straight line running in the y direction at 80% of the chord. The spanwise distance between successive tufts is $0.1s$, the first one being at the wing centerline, $y/s = 0.0$, and the 11th one at the right tip, $y/s = 1.0$. The spanwise coordinates of the origination points as fractions of s were marked on the wing for easier inspection. The length of these tufts was 12.7 mm. The second series of tufts was used for visualizing the roll up of the wing trailing vortex, and they are called here the vortex roll-up tufts (VRTs). These tufts were placed along the trailing edge of the left semispan of the wing at equal distances from the centerline to the wing tip, $0.1s$ apart. The length of these tufts was $1.5b$. To enhance the visual impression of the vortex roll up, the VRTs were chosen of various colors and the points of origination clearly marked on the top surface of the wing as fractions of the semispan. All of the force measurements were done without the presence of any tufts.

The strake model used in this investigation consisted of a delta-shaped fin having a leading-edge sweep of 67.5 deg. The chord of the strakes was 94 mm or approximately 94% of the wing chord, and its semispan was 37 mm, thus yielding an $AR = 0.81$. The total area of the two strakes was 3478 mm^2 or 21.8% of the wing area. The wing with the strakes attached had an AR of 2.84. The strake root chord was chosen somewhat shorter than the wing chord to allow for more accurate setting of the model angle of attack by visual inspection as already described; the shorter strake did not blanket the airfoil near the trailing edge as a strake having a root chord equal to the wing chord would have. The strake is shown in Fig. 1. The strakes were made of a Duralumin plate having a constant thickness of 2.54 mm thus giving a relative thickness of 2.7%. The leading edges were made sharp by applying symmetrical 30-deg bevels, or chamfers, on both sides. The attachment brackets were machined separately and then glued in place to minimize the required machining. Efforts were made to minimize the size of the brackets. Nevertheless, the drag of the attachment brackets and screw heads have been estimated and subtracted. The particular strake shape and size were chosen to provide a strong leading-edge vortex and to best fit the wind-tunnel test-section. There was a 34-mm, or $0.15b$, wide gap between either tip of the wing-strake assembly and the test-section wall. The strakes

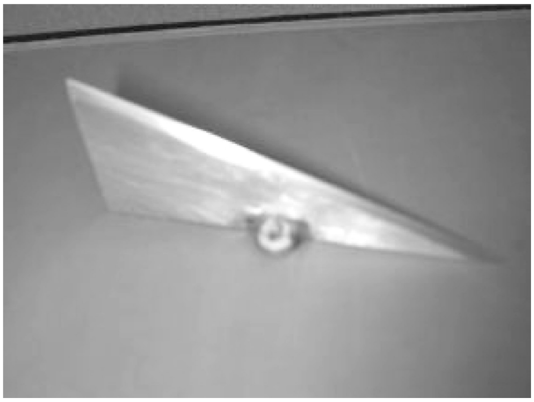

Fig. 1 Movable tip strake model.

were attached to the wing at pivot points located at 80% of the wing chord and 54% of the strake chord for all of the tests in this study. The leading edges of the wing and strake root coincided. The strakes were in the plane of the wing, that is, no dihedral was introduced by the addition of the strakes. The angle of the strake relative to the wing d_s was varied within the set 0, 5, 10, −5, and −10 deg, and for each d_s the model was tested for values of α from −5 to 20 deg with a 1-deg increment (see the following). Multiple repeated runs were run at $\alpha = 15$ deg on the models when equipped with the VRTs for vortex flow-visualization purposes. For the purpose of this visualization, limited use of an oil smoke generator was also made.

To investigate the effects of the increased aspect ratio of the wing with the tip strakes, a third model was constructed by adding two rectangular wing extensions, one to each tip of the baseline wing. These extensions had the identical cross section as the baseline wing and the span of 60 mm each. This model is referred to as the long wing. It had the same AR as the wing with the strakes: 2.84. When tufts were installed to this wing, they were placed 0.1s apart and had a length of 1.5b, s and b being for the long wing. The area increase for the long wing was 74.5% of the baseline wing reference area.

Experimental Uncertainties

The following are estimates of the uncertainty levels associated with all of the variables involved in this investigation.

The angle of attack of the wing could be determined to within ±0.25 deg. All of the lengths could be considered reliable to within 0.5 mm. The dynamic pressure uncertainty is estimated to be ±0.1 kPa. Finally, the lift-and-drag force readouts are estimated to be reliable to within ±0.05 N.

Discussion of Results

The C_L vs α curves for the three configurations, the baseline wing (BLW), the wing with the movable tip strakes (MTS) at $d_s = 0$ deg, and the long wing (LW), are shown in Fig. 2. The forces were made dimensionless using the reference areas of each wing, that is, the area of the strakes or of the rectangular extensions has been added as applicable. The standard wind-tunnel corrections, have been applied.[53] For the purpose of these corrections, the wing loadings considered here have been assumed to be halfway between the uniform and elliptic loads. The higher aspect ratio of the long wing produced the expected change in the C_L vs α curve. The two curves corresponding to the rectangular wing models, the BLW and LW, exhibit the expected linear behavior for all angles of attack up to right before stall. Furthermore, it can be seen that the lift curve for the configuration with strakes exhibits nonlinear behavior characteristic of slender delta wings and caused by the presence of vortex lift. Namely, the vortex lift produced by the strakes is known to be nonlinear (see the preceding). It can be seen from this figure that the increases in lift coefficient caused by the addition of the strakes and the rectangular wing extensions are at a ratio of approximately 1:2, or 50%, for a wide range of α, whereas the added areas are at a ratio of 21.8/74.5, or 29.3%. Thus the addition of the strakes appears to be significantly more effective from the increased area standpoint. Having in mind the structural differences, it can be concluded that the differences in added weight would favor even further the strakes over simple rectangular extensions.

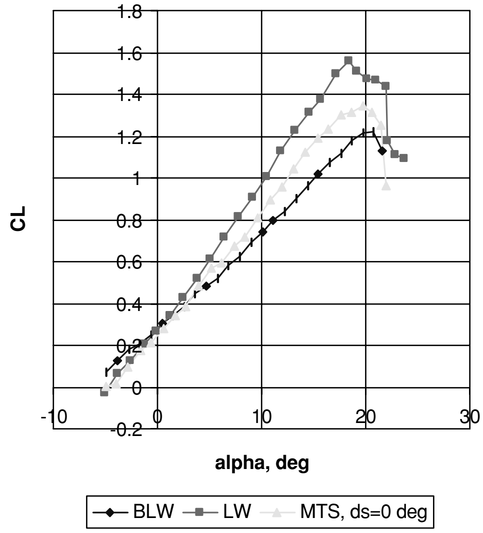

Fig. 2 Lift coefficients of three wings.

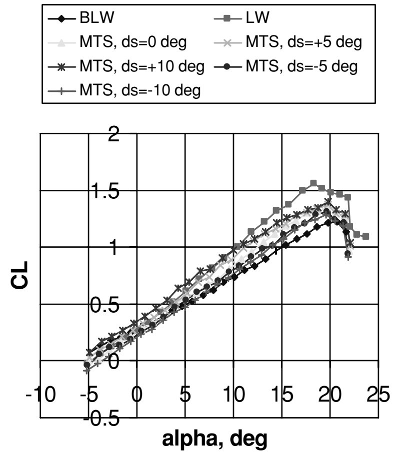

Fig. 3 Lift coefficients for seven wing configurations.

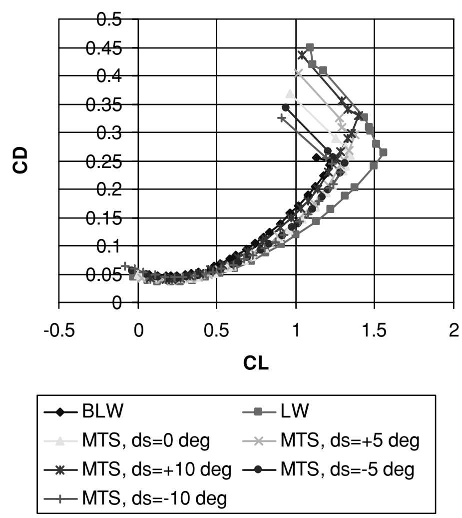

Fig. 4 Drag polars for seven wing configurations.

The C_L vs α curves for all seven configurations considered in the study are shown in Fig. 3. In addition to the three curves of Fig. 2, the curves corresponding to the two positive (strake leading edge up) and two negative (strake leading edge down) deflections of the movable tip strakes have been also added. It can be seen from this figure that the configuration with the MTSs at $d_s = +10$ deg is superior to the long wing in terms of lift coefficient over a range of lower to moderate α. Also the configuration involving negative d_s produces higher C_L than the baseline wing at higher α as it would be expected. The changes in the wing reference area caused by the deflection of the MTSs have been considered negligible. Figure 4 gives the drag polars for the seven configurations tested. It is seen that the configurations with the MTSs installed lie between the two rectangular wings, meaning that the benefits accompanying higher aspect ratios can be obtained by the addition of these strakes at a lower price in terms of increase in wing weight. In addition to the parasite drag increase, a portion of the additional drag is the induced drag caused by the higher lift generated by the configuration

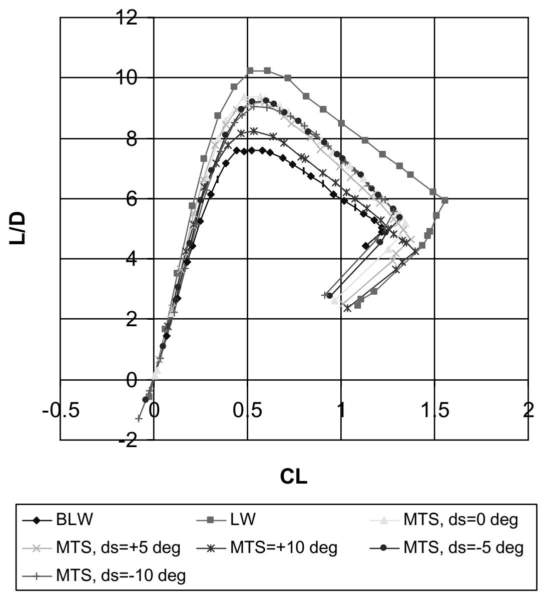

Fig. 5 Lift-to-drag ratios vs lift coefficient for seven wing configurations.

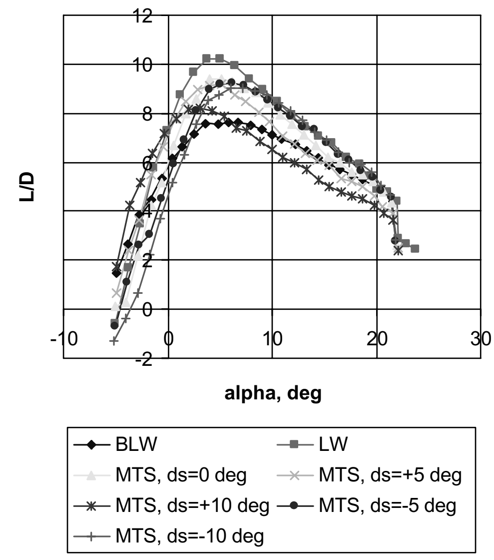

Fig. 6 Lift-to-drag ratios vs angle of attack for seven wing configurations.

with strakes. No attempts have been made to seek optimal configurations in the present study. It appears that a continued study investigating other strake sweep angles, areas, and settings would be warranted.

Figure 5 gives the lift-to-drag ratios at the same lift coefficients for the seven configurations. Once again, the MTS curves are between the curves for the two rectangular wings indicating that significant increase in the wing's aerodynamic efficiency seem achievable with the strakes. For example, the MTS, $d_s = 0$ deg configuration increases the maximum wing L/D from 7.6 to 9.4, or by 23%, with an increase in wing area of 21.8%. On the other hand, the long wing increases the maximum wing L/D from 7.6 to 10.2, or 35%, with an increase in wing area of 74.5%. When calculated on the percent-of-area-increase basis, the MTS wing increase the maximum wing L/D by 1.06 for each percent of area increase, whereas the long wing improves the maximum wing L/D by 0.47 for each percent of area increase. Thus, the MTS wing appears to be $1.06/0.47 = 2.55$ times more efficient that the long wing.

Because Fig. 5 does not give a clear answer on the relative merits of the configurations tested in the low-α region, plots of L/D vs angle of attack are shown in Fig. 6. From this figure, it appears that it would be advantageous to deploy the strakes at higher positive deflection angles while the wing flies at lower α, whereas at higher α it would be beneficial to set the strakes at negative d_s. This conclusion would appear to be the natural one because the effective angle of attack of the strakes is obviously determined by the wing angle of attack and the setting of the strakes relative to the wing, that is, $\alpha + d_s$. From Fig. 2, it would appear that this particular strake achieves its maximum lift between 15 and 18 deg. When these strakes operate at angles of attack outside of this range, their effectiveness diminishes. However, it is felt that the comparison of Fig. 6 is of limiting value because it is more significant what lift a wing generates than at what angle of attack it flies.

The profound effects of the strakes on the wing aerodynamics are explained by the presence of strong vortices springing from the strake leading edges as just discussed. These organized vortical flows generate additional lift, the vortex lift as shown in Fig. 2. As a secondary effect, the strake vortices also energize the baseline wing flow over the wing suction side near the tip region. During this study, a limited investigation has been made of the effect of the strake vortices on the baseline-wing flow separation. By observing a series of tufts, the FSTs just described, this effect was clearly observed as suppressed separation in the tip region. Based on the observations of the FSTs at $y/s = 0.9$ and 1.0, it is believed that the presence of the strakes and the accompanying vortices energized the flow in the tip regions and kept it attached to higher angles of attack. This phenomenon should be further investigated. Therefore it can be argued that the tip strakes as used here not only provide additional lift but also change the existing lift distribution of the baseline wing in a favorable manner.

Apparently d_s represents a completely new degree of freedom in controlling the aerodynamics of the wing-movable strake configuration, that is, the strakes can be set at an optimal d_s for any α. Movable tip strakes thus appear to be suitable for optimization in conjunction with an onboard computer. Then the strake deflection could be programmed, or scheduled so that the airplane always flies at, for example, the maximum available C_L/C_D, or maximum $M(C_L/C_D)$, M being the Mach number, thus optimizing its endurance or range performance. At other times it might be desirable to generate the highest lift available.

Another area of possible application of the movable tip strakes is that of lateral control. By asymmetric deflection the resulting lift changes on the two semispans, because of both the added strake lift and the change in the main wing lift distribution, acting at large distances from the airplane x axis could produce large rolling moments. With very high symmetrical deflections the device can also have potential for use as an aerodynamic or speed brake. Further studies of these areas are needed.

As a possible replacement for either the traditional trailing-edge flaps or ailerons, it is believed that the movable tip strakes would offer significant improvements. It can be concluded that the additional lift at the tips of the main wings would produce larger root bending moments and thus require a heavier wing structure. To address this issue, it is noted that the structure of the strake itself would contribute little to the wing weight. Also the actuation of the strake would require simpler mechanisms than the traditional flaps do. Thus, it is felt that the combined effects on the specific excess power would be favorable. The idea seems to be especially attractive for implementation on airplanes of shorter wing spans. Carrier-based airplanes, where the space for parking airplanes on the deck is at a premium, and aerobatic airplanes seem to be two classes where this concept could potentially be of interest. Thus it is believed that this idea warrants further detailed studies. Other wing and strake cross sections and planforms should be included. The effect of adding dihedral and anhedral should be explored.

A part of the study has been devoted to investigating the possible effects of the strakes of the trailing vortex rollup. It was limited to the near-field portion of the wing flowfield up to $1.5b$ behind the trailing edge. For that purpose repeated tests were run at $\alpha = 15$ deg with the baseline wing and the MTS-equipped wing. This particular

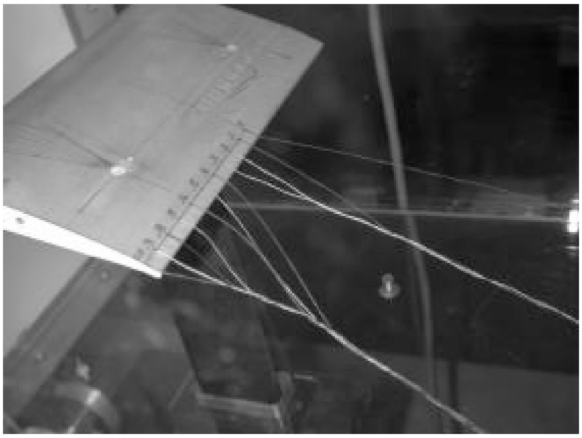

Fig. 7 Trailing wake vortex rollup, baseline wing, $\alpha = 15$ deg.

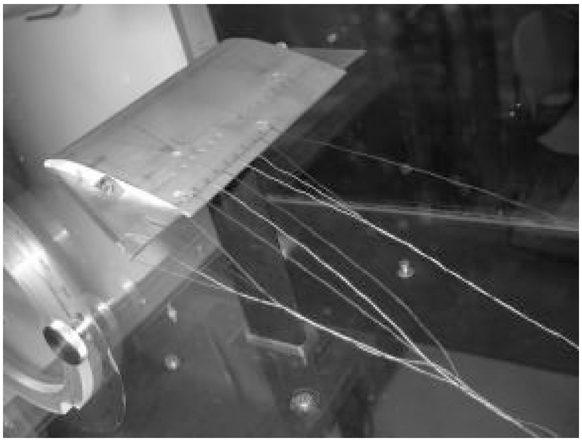

Fig. 8 Trailing wake vortex roll up, wing with MTS at $d_s = 0$, $\alpha = 15$ deg.

angle of attack was chosen as a value believed to be representative of takeoff and landing, that is, those phases of flight when trailing wake vortices are of most concern for their ability to produce conditions hazardous to following aircraft. For these runs, the wings were equipped with the tufts just described and the disposition of the tufts observed and photographed. Two such photographs are shown in Figs. 7 and 8 for the baseline wing and the wing with strakes at 0 deg, respectively. The strength of a trailing vortex in the near field can be described in terms of the number of tufts representing vortices, or vortex filaments entrained in the outer vortex rope and the distance from the wing trailing edge to the point at which a compact vortex starts. This approach has been used to very effectively quantify the trailing vortex strength in a recent study by the author.[54] It can be seen from these two photographs that the outer vortex ropes comprised seven tufts in both cases. For repeated runs the starting point for the baseline wing was measured to be 60 mm, or $0.37b$, whereas for the wing with strakes it was found to be 141 mm, or $0.6b$. Thus it would appear that the trailing vortex generated by the wing with the MTSs installed was less organized and thus weaker than the one produced by the baseline wing. Actually the strength of the vortex is inversely proportional to this distance. As shown in Ref. 54, this inverse proved to be a reliable measure of the vortex strength. The values for the two cases considered here are $1/0.37 = 2.7$ and $1/0.6 = 1.67$. The ratio of the two results is $2.7/1.67 = 1.62$, which would indicate that the baseline wing vortex is 62% stronger than the vortex from the MTS-equipped wing.

Figures 9 and 10 show oil smoke visualization results for the baseline wing and the wing with the MTS at 0 deg, respectively. The tuft arrangement shown in Fig. 10 was abandoned and replaced by the one shown in Fig. 8. It can be seen that the baseline wing

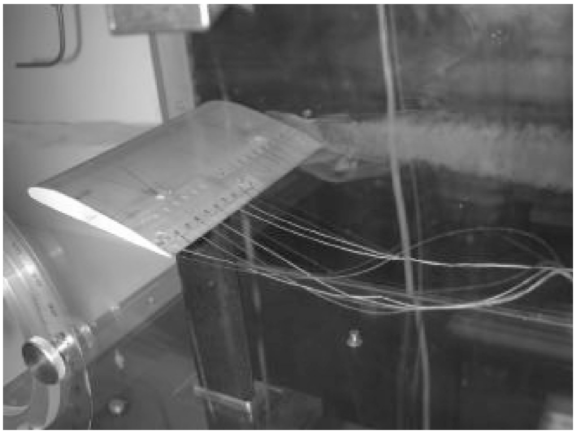

Fig. 9 Trailing vortex of baseline wing, $\alpha = 15$ deg.

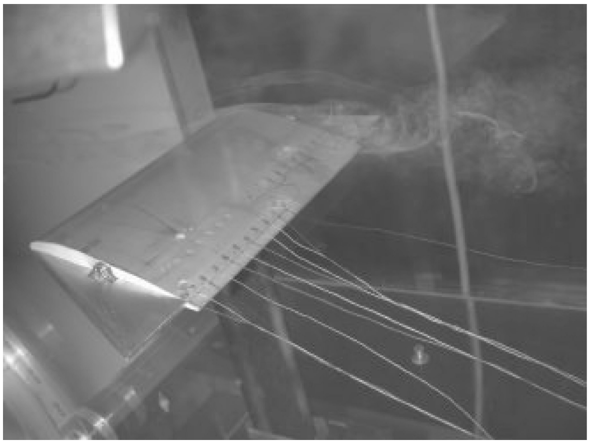

Fig. 10 Trailing vortex of wing with MTS at $d_s = 0$, $\alpha = 15$ deg. (Note: Tuft arrangement shown here was abandoned and replaced by the one shown in Fig. 8, see text.)

Fig. 11 Simple vorticity meter.

vortex exhibits a much more organized structure in the near field than the vortex shed by the wing with the strakes. Thus this result is in agreement with the one just discussed as well as with the findings of Staufenbiel and Vitting.[36] The limited scope of this portion of the present study should be kept in mind. It is felt that a more extensive study along these lines is warranted.

Figure 10 also shows the strake vortex. A simple technique was used to quantify the strength of this vortex. A four-vane vorticity meter was constructed (Fig. 11) and used in combination with a Shimpo digital stroboscope model DT-301. At $\alpha = 15$ deg the rotational speed of the strake vortex averaged 1758.8 revolutions per minute, while the wing trailing vortex rotation reached an average of 2396.9 rpm. The trailing vortex generated by the baseline wing, on the other hand, averaged 3940 rpm at the same flow conditions. The ratio of the two angular speeds is 1.64. This would suggest that the baseline wing vortex turns 64% faster than the vortex generated by the wing with the strakes. The result is so close to the ratio of 1.62 already found when the vortex rope starting points were considered that the author believes that the agreement is fortuitous. Nevertheless the potential of movable tip strakes as a vortex attenuation device clearly deserves further studies.

Conclusions

The effects of movable tip strakes on the aerodynamics of a rectangular wing have been investigated in a wind tunnel. The addition of two slender delta-shaped sharp-edged flat-plate strakes significantly modified the flowfield around the wing and improved its aerodynamic characteristics. The strakes having an area equal to 21.8% of the reference wing area improved the wing's lift-to-drag ratio by 23% giving a 2.24 times better improvement on a per-percent-increase-in-area basis than a rectangular wing having the same aspect ratio. It is believed that the added wetted area and mass will be more than compensated for by the performance gain. The addition of the movable strakes provides an additional degree of freedom in controlling the wing's aerodynamics and appears to open new possibilities for optimization of wing design and operation, particularly for wings having shorter spans. There are some indications that this device might favorably affect the near-field roll up of the trailing wake vortices. Further studies are needed to investigate the effects of other strake planforms, pivot locations, and deflection angles, in combination with wings having other airfoils and planform shapes.

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